PROGRESS REPORT - FERMILAB ENERGY DOUBLER

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I. INTRODUCTION

This report will update the Progress made on the Fermilab Energy Doubler/Saver. Since the last report made to this Conference in 1976, over 100 22 foot long coils have been constructed and studied. About 50 complete magnets have been constructed in the Magnet Fabrication Facility by techniques that routinely turn out 5 magnets/week and can be easily expanded to 8/week. The tooling is such that it can be easily duplicated.

A quadrupole has been developed and tested using the same mass production techniques as are used for the dipole, and a production line to produce it is currently coming into operation.

A string of twenty-five magnets have been installed in the Main Ring tunnel and is undergoing cryogenic tests and beam transport tests at 100 GeV.

Three satellite refrigerators for the first sextant of the machine are installed and being tested and the Main Refrigeration plant is 80% complete and will be brought on-line in 1979.

Finally, a Magnet Test Facility has been constructed using a 1500 watt refrigerator that has six stations available for cooling and testing complete magnets. This facility will be able to provide complete tests of both the field quality and the cryostat, before each magnet is installed.

This report will try to provide an overall description of the progress made, and the individual reports that follow will give more complete details.

II. DIPOLE PROGRAM

The dipole for the Energy Doubler/Saver is 22 feet long, has a central field of 42.5kG, stores .5 mega joule of energy at full field, and has a useful field region that is approximately $\pm$ 1" about the axis. A cross section is shown in Figure 1. The main thrust of the development program has been to find means to construct these dipoles inexpensively and accurately. Hence, there was never any effort to construct one or two models very carefully using highly skilled labor to verify the magnetic field quality. Since Maxwell has provided the means to calculate the field shape (there is no saturated iron anywhere in the magnet), the problem is simply to get the conductors in the correct position. At first it was thought that the conductors would have to be placed correctly to about $\pm$ .001". However, a new philosophy has developed from our experience.

First, tooling has been developed that makes the coils in a highly reproducible geometry. Measurement of the completed coil then discloses errors in the geometry. These errors are used to correct the shape of the subsequently produced coils by small changes in the angles of the current blocks. This process converges rapidly and the "noise" in the manufacturing process then determines the field quality. It is the reduction of this noise to a minimum, while retaining inexpensive mass production techniques that has been the goal of the magnet development program. The magnets produced in the early stages, which are not of "machine quality", have been used for system tests of cryogenics and for development of a suitable power supply that can both power the magnets at 4500 Amps as well as protect them in case of quenches. These developmental magnets are also suitable for use in the external beam lines.

Coil Fabrication

The coils consist of two layers as seen in Fig. 1. The angles of the current blocks are such that the good field region is maximized. The coil is manufactured in the following fashion. Cable, as received from industrial sources, has been double wrapped with .001" Kapton film over which is spiral wrapped a glass tape that has been impregnated with B-Stage epoxy. The insulation is tested at 1,000 volts as the coil is manufactured. The inner coil is wound around a precision inner key as a flat "pancake" between two thin sheets of .030" iron. The assembly is then placed in a 22' long 1,000 ton press and the coil is forced into a precision mold, heated and cured under pressure.

The intermediate "banding", which is G-10 strips with slots in between to allow helium to percolate through the coils, is then put in place. The outer coil is now wound using the inner as a winding mandrel. Finally, this entire package is again placed in a precision mold 22' long situated in a 1,000 ton press, and is heated and cured under pressure. This then completes a "half coil".

The second half coil is formed in the same fashion except that 1/2 turn of the outer winding is left out and instead a single conductor is molded into the last 1/2 turn of the outer coil at the parting plane. This conductor forms the "return bus" for the current in a string of magnets. Each magnet has two leads at its upstream end and two at its downstream end. This allows the magnets to be connected in series without the necessity of a warm-cold current lead transition or the complication of a cold distribution bus system. A more complete discussion of coil fabrication is given in paper JC-4.

Support Structure

Two half coils are then assembled together, covered with a triple overlap of 0.010 in Mylar (to be changed to Kapton for radiation resistance) and placed inside precision stamped stainless steel "collars". These interlocking collars furnish the main support skeleton to contain the large magnetic forces. For instance, a conductor typically has nearly 100 lbs. per inch of magnetic force which must be sustained by the support system.

The collaring system is a major innovation. The pieces are inexpensive, can be mass produced with high accuracy (tolerances of the order of a few tenths of a mil) and their interlocking nature makes them very strong and easy to assemble by halves. After a loose assembly is made, the coil and collars are placed in a third 1,000 ton press. Precision support pieces push the collars completely together. This requires a force of about 5,000 lb/in. of length due to the fact that the coils are larger than the collars. The system is elastically compressed until the collars are closed at which point they are welded with three welds along the interlocking fingers on each side. The compression is sufficient so that the mechanical forces from the collars exceed the magnet forces. This was a difficult problem to solve due to the contraction of the coil being more than the collars during cool down. This problem was solved by very carefully adjusting the size to which the coils were molded, as well as the mold temperature and pressure. It is found that any heating of the coil above 50°C causes the relaxation of this preload. The fact that this problem is solved is attested to by both magnetic measurements of the multipole moments as a function of current as well as direct measurement of the coil motion during excitation. Finally, the coil is placed on a flat table and measured for twist. After straightening, the collars are painted with room cure epoxy which makes the structure much more rigid in torsion and locks adjacent collar laminations together.

Extensive calculations and measurements have been made of the deflections and stress levels in the collars. The results may be found in Paper JC-4. Fatigue tests made at 80K show the collars should survive over 10 cycles.

The coil at this point is ready for the cryostat. The winding and collaring operations have required 250 man hours. Over 80 of these coils have been given vertical dewar tests at this stage where training, ramp rate dependence, deflections, and quench behavior are studied. This program is a research effort only and will not be necessary for every magnet.

Cryostat

The cryostats are partially assembled and tested in the plants of external fabricators. The coil is inserted into its cryostat and at several points vacuum and electrical insulation tests are carried out. The final assembly is leak tight among the five separate compartments - beam tube, single phase helium, two phase return helium, N_2 intermediate shield, and insulating vacuum - to a level of 2×10^{-10} atm cc/sec (helium) torr. liter/sec. The coil is tested for electrical breakdown at 3,000V. See paper CA-13.

Yoke

Finally, the cryostat and coil assembly are placed in the iron flux return yoke. The yoke is carefully measured and fit to the cryostat since the basic centering forces for the coil must come from the yoke. The support pieces are G-10 and there are 9 stations per magnet providing an elastic restoring force constant of 125 lb./mil. at each station. They are the main source of heat leak in the dipole and account for 4 w/magnet. The decentering forces due to the magnet field amount to 1.1 lb./0.001 in. (displacement) for each linear inch of coil. Decentering results mainly in quadrupole errors in the field - the higher multipole contributions being negligible due to the large distance between the iron and the active field region.

The yoke at present is 12 in x 15 in with a 7-1/2 in bore. It is stacked on a curved stacking fixture and the two halves forced around the cryostat and coil assembly. This results in a curved magnet, thus eliminating the sagitta of 0.5cm that would exist in a straight magnet. A considerable amount of waste results from stamping these laminations and a "no waste" shape has been devised and is being measured. A small amount of the iron in the lamination reaches the saturation level, however, the iron seems far enough away from the bore so that no undesirable effects seem to propagate into the beam region. Almost $300,000 can be saved if this lamination can be used.

Testing Program

The testing program has been divided into several independent efforts - vertical testing of the magnet coil, sans yoke, and cryostat, a complete analysis at the Magnet Test Facility, and systems tests to develop the pertinent information for design of the cooling system and the power supply and associated protection system.

Vertical Dewar Tests

In a vertical dewar test the coil is placed in a vertical dewar with boiling H_3 at atmospheric pressure. Quenches, when they occur, are detected and the power supply disconnected and the energy discharged into an external resistor. This generates an exponential discharge and a voltage of 2,000 volts across the coil terminals. The coil is instrumented to measure the change in diameter of the support collars during excitation and to record the motion of the wire of the inner coil next to the key. The number of quenches to train the magnet to its short sample limit, and the quench current vs. ramp rate are measured. These results are shown in the following Figures.

Figure 2 shows a typical training curve. The wire for each magnet is tested and its short sample characteristics measured (shown in the insert). At this point, the high field point occurs at the inside end of turn of the inner coil. (Later, when the coil is in a yoke, the high field point is at the inner key.) A histogram of 20 coils tested is shown in Figures 3 and 4.

Figure 5 shows the deflection of the collars. The change in diameter is measured by means of calipers read out by strain gauges. The insert shows this change for a typical magnet vs. current which is very accurately parbolic as it should be. The histogram shows the behavior of a number of coils. A similar mechanical measurement measures the motion of the wire of the inner coil with respect to the key in the collar to verify directly that the coil has not lost its preload.

Additional measurements in this test are being superseded by those now being made at the Magnet Test Facility, which will be discussed below. See paper CA-15, 16.

Magnet Test Facility

At the outset it was realized that the ultimate verification of a properly constructed magnet can only be obtained by cooling it down and exciting it to full field. Consequently a Test Facility was constructed with six measuring stations using a 1,500W refrigerator. A magnet can be installed in a measuring station in four hours and cooled down in another four. Measurement at present takes about eight hours but this still represents a research program and is more complete than will be ultimately necessary. At present after cooling down and verifying the integrity of the vacuum system the following measurements are made:

1. Ramp rate dependence of the quench point.
2. Magnetization loss in magnet as a function of peak field.
3. Ramp rate dependence of loss.

4. Harmonic Analysis.
5. $\int B \cdot dl$ vs. current.
6. B vs. z using NMR probe at 2T.
7. Orientation of field relative to the yoke and marking with survey flags.

The ramp rate dependence has given us a considerable amount of trouble. Early in the program, one foot test magnets were built which showed essentially no ramp rate dependence at ramp rates as high as 1T/s. More recently, the full size magnets have shown serious degradation at ramp rates as low as 0.2T/s. Fig. 6 shows the variation between good and poor magnets. The source of this change has been traced to eddy current losses in the coil cable.

The cable is made up of 23 strands of 0.027 in. diameter wire which has been coated with Stay-Bright. The inter strand resistance is low. Our early coils did not have sufficient pressure applied to them during the collaring process to ensure that when the magnet was cold there would be a preload on the coil greater than the magnet forces. In such a "floppy" coil the contact between strands would be poor, and hence eddy current losses in the cable would be low. The problem of preload was attacked and solved as described previously. However, the strands of the cable are now in excellent contact with each other and the eddy current losses become unacceptable. The losses cause heating in the magnet that increases with B and gave a bad ramp rate dependence to the coil. The obvious solution was to increase the inter-strand resistance while still keeping some contact between the conductors in order to help ensure current sharing among the strands. To this end we have tried several experiments, and several solutions have been found. The best seems to be giving the wire a treatment with Ebonol-C producive CuO layer. Table I lists the various magnets constructed and the loss in joules per cycle for a peak field of 4T and a ramp rate of .2T/sec. "Bismuth" means we tried to "poison" the Stay-Bright by dissolving 5% Bi in it. "Zebra" means cable made with 1/2 of the strands coated with Ebonol. This effectively breaks up strand-to-strand conduction, but leaves the top and bottom layers of the cable crossing in conducting loops. "Kapton" means that the Rutherford cable was formed over a 0.001 in. thick piece of Kapton 0.250 in. wide. (The Kapton survives the turks heads!). This essentially insulated one side of the cable from the other but left strand-to-strand contact through the Stay-Bright. Since the outer winding is in a much reduced field, we built two "graded" magnets with inner Ebonol coils and outers in the regular Stay-Bright configuration. The losses for a typical Stay-Bright coil made the same as the test series is shown for comparison.

Some typical measurements of the loss vs. peak field and at a fixed peak field vs. $\dot{B}$ are shown in Fig. 7. For a triangular excitation, the losses should approximately follow the expression:

$$\text{Joules/cycle} = \alpha B_{max} + \frac{\dot{B} B_{max}}{R}$$

The first term is the hysteresis losses, the second is the eddy current losses. Fig. 7 also shows the dramatic effect of the Ebonol insulation effectively reducing the eddy current losses to zero. RDD114 a normal Stay-Bright magnet is shown for comparison.

Harmonic Analysis

About 40 magnets have had a harmonic analysis made of their field. Roughly 20 of these only had their central field measured with a 4 foot long coil. The other 20 have each had a set of 3 overlapping measurements made with a coil 8 feet long - one in the center and one at each end. These three measurements can be combined to give an average through the magnet.

A brief word concerning the theory of the design of the magnet is in order here. First of all, if there are no construction errors, then by symmetry all of the skew multipoles are missing as well as the series of normal terms, quadrupole, octupole, etc. So we can expect the size of these terms to give some indication of the errors inherent in the magnet. Next there are two angles associated with the inner and outer coil, and hence the normal sextupole and decapole can be adjusted to zero in the body of the magnet. However, the ends must now be considered and here one finds a very strong sextupole moment plus some decapole. Hence, the angles are adjusted to eliminate the sextupole and decapole in the integral of B through the magnet. The resulting field is fairly rich in higher multipoles. Table II below shows the calculated multipoles in the body of the magnet as well as the average through the magnet including the ends. The units are in 10^{-4}T at 2.54cm when the central field is 4.5T.

We can now address the question of how well the present output from the "Magnet Factory" is matching the theoretically desired magnet. To clarify the nomenclature, we write here the field expansion used.

$$B_y(x) = B_o \sum_{n=0}^{\infty} b_n x^n$$

$$B_x(x) = B_o \sum_{n=1}^{\infty} a_n x^n \qquad \text{multipole number} = 2(n+1)$$

The terms in the expansion are measured up to the 30-pole term (n = 14). It is well to remember that a given multipole can be represented everywhere on a circle of radius r by a vector of fixed length but variable direction. The vector rotates n-times in proceeding around the circle and its length is proportional to r^n.

Two additional points are worth making. First, the field expansion is rich in harmonics. The higher harmonics essentially result from the sharp corners of the coil. We have very little control over these harmonics - errors in the winding would have to be pathological to strongly influence the n = 14 term. Hence, for these harmonics we can rely on theoretical calculations to tell us how important they are at any given radius provided we are not too near the coil. In our case, we find that at a radius of 1 in. the n = 14 term has $b_{14} \approx 10^{-5}$ or at a central field of 4.5T $B_o\, b_{14} \approx .4$ gauss. The higher terms are even smaller. Thus, everywhere inside of a 1 in. circle we will know the field to a relative accuracy of 1 part in 10^5 if we measure out to n = 14.

The second point is very important, and that is that the key angles effect mainly the low order harmonics, i.e., quadrupole, sextupole, octupole, decapole. Since these are easily adjustable, we see that we have a means of correcting systematic errors in the coils as they are manufactured. Thus, if the coils are made in a reproducible fashion by the "factory" we now are able to feed back measurement information to correct these low order multipoles.

Another way to summarize this is to say that any shape "near by" the desired shape of coil will have the same high harmonics as the "perfect" coil, but a different set of lower harmonics. However, these lower harmonics can be corrected in our coil by easily adjusted shims at the keys to produce the desired terms. It is in this fashion that we avoid having to produce coils with an absolute accuracy of the order of 0.001 in.

Now to examine the coils. Figures 8 and 9 show the average a_n and b_n of a set of 13 magnets in the series from 100 to 120. The horizontal axis is n and the vertical axis is $B_o\, a_n$ and $B_o\, b_n$ for $B_o = 4.5$T. The error bars show the rms fluctuation about the average values. If there were no errors in the magnets, all of the a_n would be equal to zero as well as the odd b_n. It is seen that the major fluctuations occur in the quadrupole, sextupole, and octupole terms. This supports the thesis set forth above that these terms are mainly determined by the gross geometry of the coil. The even b's should not be zero and the values calculated for them are shown in Table II.

It is seen in this set of magnets that the skew and normal quadrupole are both fluctuating about the same amount. (Table III gives numerical values.) The error driving a_1 is probably the asymmetry in the size of the top coil vs. the bottom coil. Each 0.001" that the "parting plane" deviates from perfect symmetry gives approximately 5 gauss at 1 in. for $B_o\, a_1$. Similarly a right left assymmetry of the key angles of the inner coil of 0.002 in., we find, gives $B_o b_1$ approximately 5 gauss at 1 in. Also the quadrupole is driven by displacement of the whole coil bundle from the center of the inner yoke. Calculation gives 1 gauss for the magnitude for each 0.001 in. displacement (in the obvious direction.) At present we think These errors are not out of line with our present construction errors.

The sextupole term b_2 is seen to be much too negative. This has been traced to the ends cohibiting a much stronger sextupole than calculations would indicate. At present, the details of this discrepancy are not understood. However, this effect can be corrected in the manner described above by compacting the inner and outer coils slightly more by means of shims at the keys. In this case we calculated an inner coil shim of 0.007 in. and one for the outer of 0.016 in. This change was made and the average coefficients of magnet #130 and 131 indicate that this change has corrected the trouble.

In addition to the harmonic analysis, the B_y (z) is measured at 2T with an NMR PROBE. Short term fluctuation of the order of $\pm$ .05% are evident and reflect errors in the conductor placement. The average value for 14 magnets is 9.984 $\pm$ .004 gauss/amp. The error if attributed completely to random fluctuations would indicate that the radius is fluctuating by $\pm 1.3 \times 10^{-3}$ inches.

The $\int B \cdot dl$ at various currents is also measured by stretching a single wire loop through the bore of the magnet and integrating the coil output as the magnet is ramped. The coil is flipped at zero current to measure the residual field due to persistent currents. The $\frac{1}{I}\int B \cdot dl$ shows systematic effects due to persistent currents andd very small non-linearities from the iron. This will have to be studied in more detail in order to ensure that the quads and dipoles track. The average of $\int B \cdot dl$ for 10 magnets between units 110 and 130 is 9.985 $\pm$ .005.

Measurements are being undertaken to determine how stable the field is to temperature cycling and quenching. Due to the large amount of stored energy in a magnet, it is difficult to run meaningful life tests. However, mechanical cycling tests at low temperature are possible and are being carried out.

Quadrupole

The first quadrupole was a three shell quadrupole with the windings being wound somewhat after the BNL style. Eight such quads were built and tested. The experience with them was somewhat similar to that with dipoles. With the completion of the eight three-shell quads we have switched production to a two-shell quad with a spacer in the inner coil to help control the harmonic content of the field. The first model of this coil has just been tested and after two quenches we were unable to follow its training beyond the 5400 amps limit set by the power supply. The coil package is well clamped and shows no evidence of motion under magnetic forces. Complete measurements are underway.

The quad-package also houses the beam position detector, the tune quadrupole, the vertical and horizontal dipole and sextupole correction coils. The safety lead for magnet protection and liquid helium and nitrogen connections are made, when necessary, in this box.

Present Program

The present program has the following major goals.

1. Increasing dipole production from 5 to 8 magnets/week, while controlling the quality. Every magnet will be tested and pass acceptance criteria.

2. Complete the new quadrupole assembly line.

3. More tests on strings of magnets under Laboratory conditions to verify that the magnet power supply and quench protection scheme is satisfactory. (Paper JC-8)

4. A major effort is underway to install a full sector of the machine. It will allow us to investigate injection into a string of 160 dipoles and study the cryogenic problems of the first large installation of superconducting magnets. Twenty magnets are now installed and cold and early '79 should see the sector complete. An ingenious scheme conceived by T. Collins will possibly enable us to achieve the circulating beam through this sector. The experience in the tunnel has been as follows. Two men for one hour can transport and set a magnet in place. One man two hours to connect vac/He/electrical connections. Two men two hours to align. Leaks have occurred once about every 4 magnets. It is expected this will decrease as the crews become more experienced with cryogenic magnets.

5. Finish the central helium liquifier and bring it on-line.

Future Challenge

On the basis of our experience so far we can identify the new challenging problems that a 5 TeV or greater energy machine poses.

1. Develop an 8.0T (or more) magnet.

2. Perfect schemes to make an inexpensive "extruded" magnet of high quality. Since only the cross section is important, the tooling should reflect this and become independent of length.

3. Develop the technology of handling beams in a small aperture. It is well known that the aperture in the past has been determined by the need to inject, extract, stack, etc. However, with large fields, the forces become very large and the energy density high. In addition, with superconducting magnets, the energy necessary to quench may only be fractions of milli-joules/cm^3, while the beam may store 10 M joules or more. The tendency is to want a large aperture to keep the beam halo away from the magnet! However, a small aperture is strongly indicated by magnet cost, by large constraining forces, and by the large energy density in an 8T magnet.

It will be a real challenge to reconcile these conflicting requirements and invent solutions using the new magnet technology.

This is a report on the combined work of many people at Fermilab. Some of this is indicated by references to other papers given at this conference. However, I would like to acknowledge that the guiding hand of R.R. Wilson prevades all of the work and the sculptural beauty of the magnets attests to his presence.

TABLE I.

Joules/Cycle (B_m = 4T, $\dot{B}$ = .2T/sec)

	1	2	3	4	5
Hysteresis	400	400	300	390	410
Eddy Current	0	30	0	100	720

1. Ebonol
2. Ebonol Inner Coil
   Stay-Bright Outer
3. Zebra + Kapton
4. Zebra
5. Stay-Bright

TABLE II

Normal Multipole Moments* as Designed and Measured

	b_2	b_4	b_6	b_8	b_{10}	b_{12}	b_{14}
Body	24	12	21	-55	17	- 4	.3
Integral	.2	4	20	-54	16	- 4	.3
Measured	-60 ± 38	10 ± 5	16 ± 2	-59 ± 2	20 ± 1	- 5 ± 1	.1 ± .5

*Units gauss at 1: when B_o = 4.5T.

TABLE IIIa

Skew Multipole Moments as Measured (13 Magnets)

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}
av	7	2	.3	-.1	0	0	-.4	-.2	.1	-.5	.3	.7	.3	-.1
rms dv	13	2	4	.7	1.5	1	2	3	.2	1	.6	.9	.8	.6

TABLE IIIb

Odd Normal Multipole Moments as Measured (13 Magnets)

	b_1	b_3	b_5	b_7	b_9	b_{11}	b_8
av	11	3	.7	1	-.1	-.1	.1
rms dv	16	2	1	2	.2	.6	.7

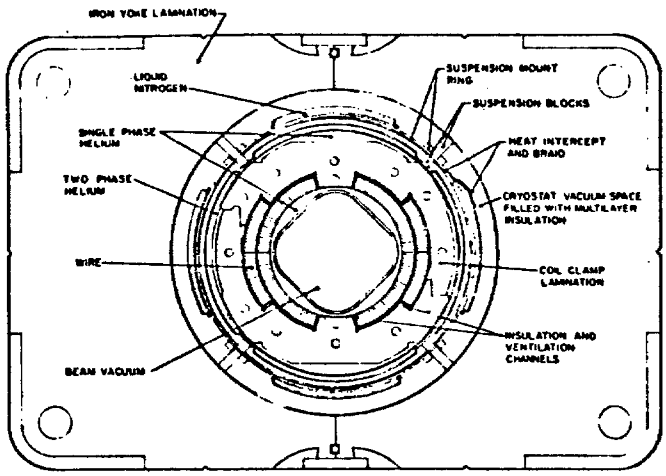

Figure 1. Dipole Magnet Cross Section.

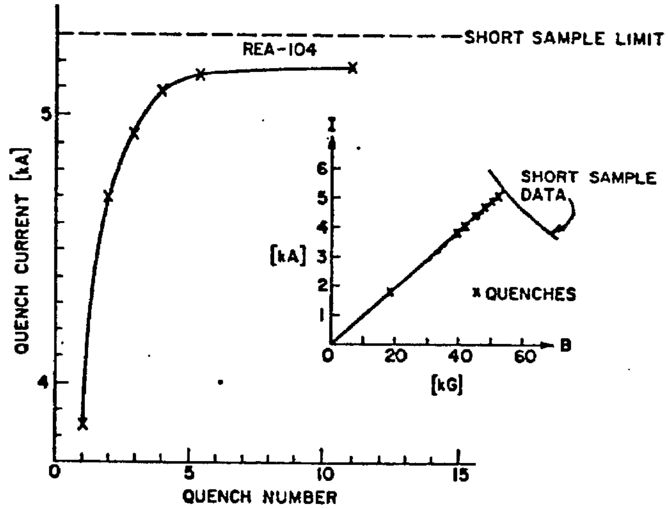

Figure 2. Training Curve.

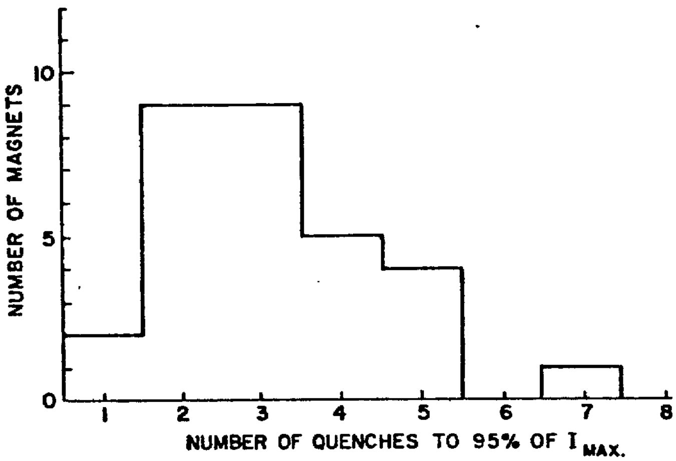

Figure 3. Training Current Distribution.

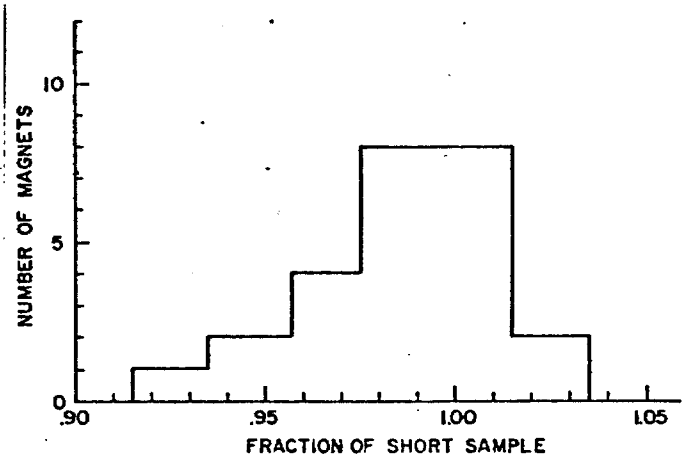

Figure 4. Distribution of Final Training Current as a Fraction of Short Sample Limit.

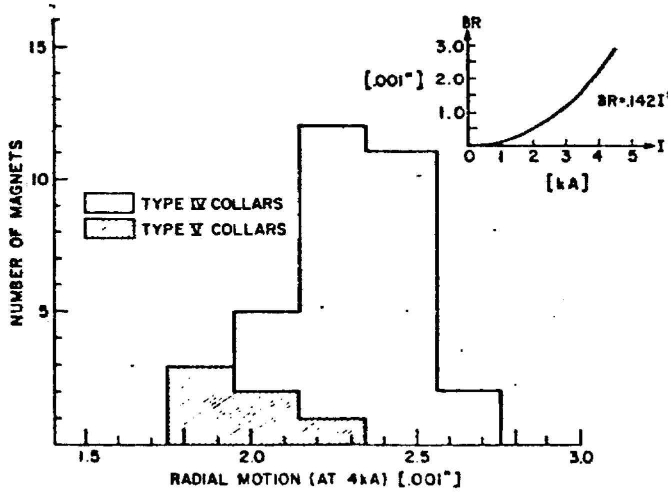

Figure 5. Elastic Radial Deformation

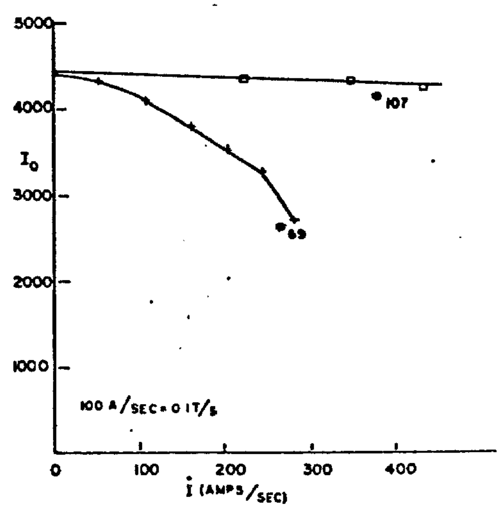

Figure 6. Quench Current vs. Ramp Rate

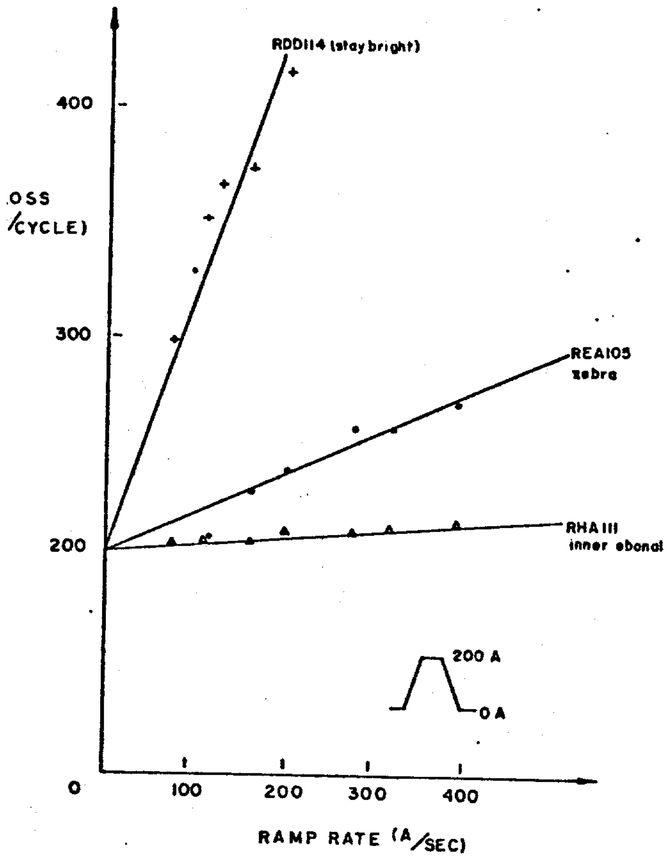

Figure 7. Energy Loss vs. Ramp Rate.

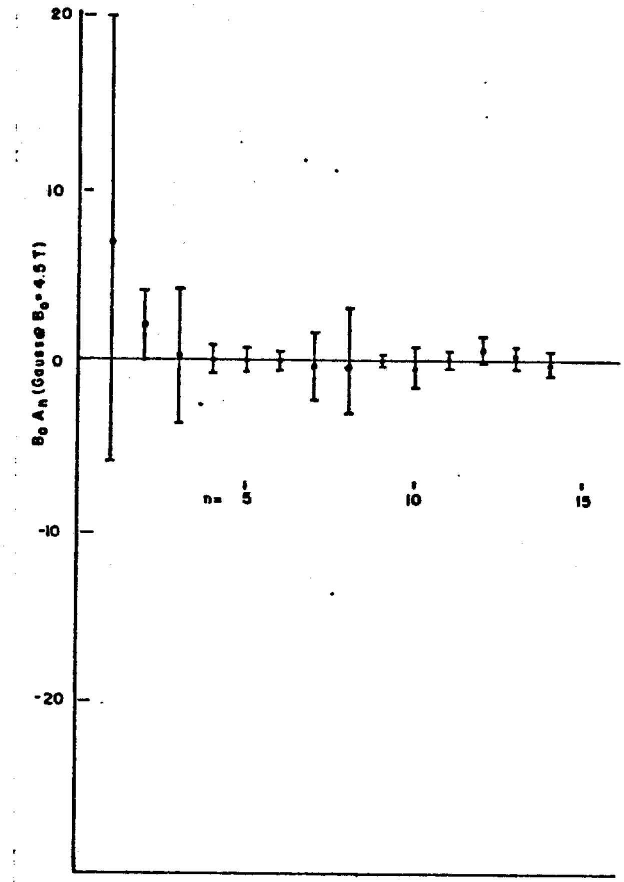

Figure 8. Skew Components at 3T Bore Field.

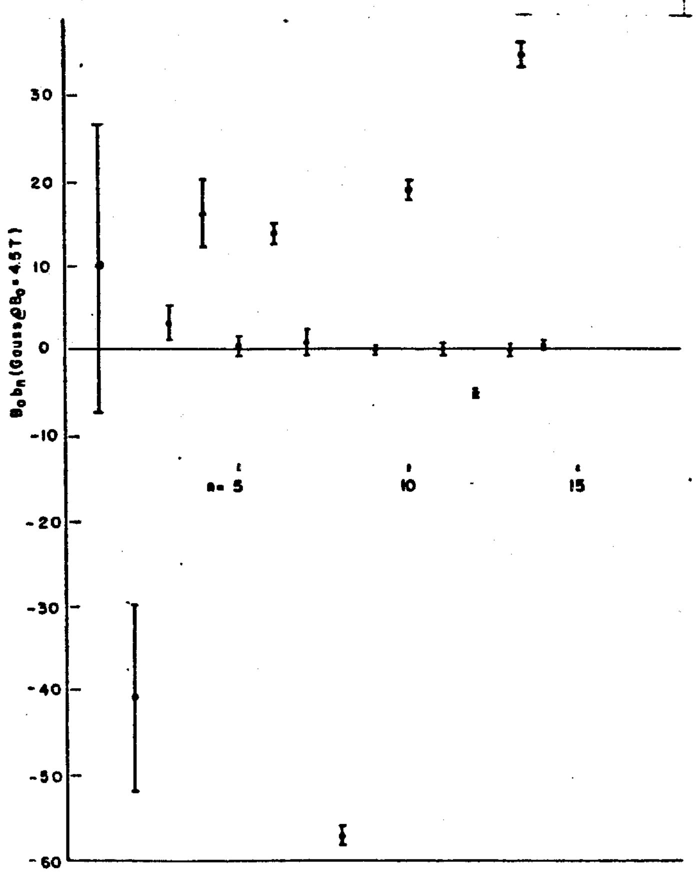

Figure 9. Normal Components at 3T Bore Field.